Phy489 Lecture 2

Standard Model Particle Masses

Fermions

(spin ½)

Matter particles

0.511 MeV/c² 106 MeV/c² 1777 MeV/c²

$$\begin{pmatrix} \mathbf{e} \\ \nu_{\mathbf{e}} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \mu \\ \nu_{\mu} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \tau \\ \nu_{\tau} \end{pmatrix}_{\mathbf{L}}$$

All neutrino masses ~ 0

~150 MeV/c² ~1.5 GeV/c² **~175 GeV/c²**

$$\begin{pmatrix} \mathbf{u} \\ \mathbf{d} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \mathbf{c} \\ \mathbf{s} \end{pmatrix}_{\mathbf{L}} \quad \begin{pmatrix} \mathbf{t} \\ \mathbf{b} \end{pmatrix}_{\mathbf{L}}$$

~150 MeV/c² ~300 MeV/c² ~4.5 GeV/c²

Bosons

(spin 1)

Force carriers

M_{higgs}= 125 GeV/c²

γ massless

$\mathbf{W}^{\pm}, \mathbf{Z}^{0}$ M_W=80.42 GeV/c², M_Z=91.2 GeV/c²

$\mathbf{g}$ massless

Running of Coupling Constants

“Coupling constants” actually change with energy, differently for the three fundamental interactions that we will deal with.

QED: photons carry no charge so do not interact with each other
(there is no photon-photon coupling or photon self-coupling)

QCD: gluons carry colour (and anti-colour) so they interact with each other

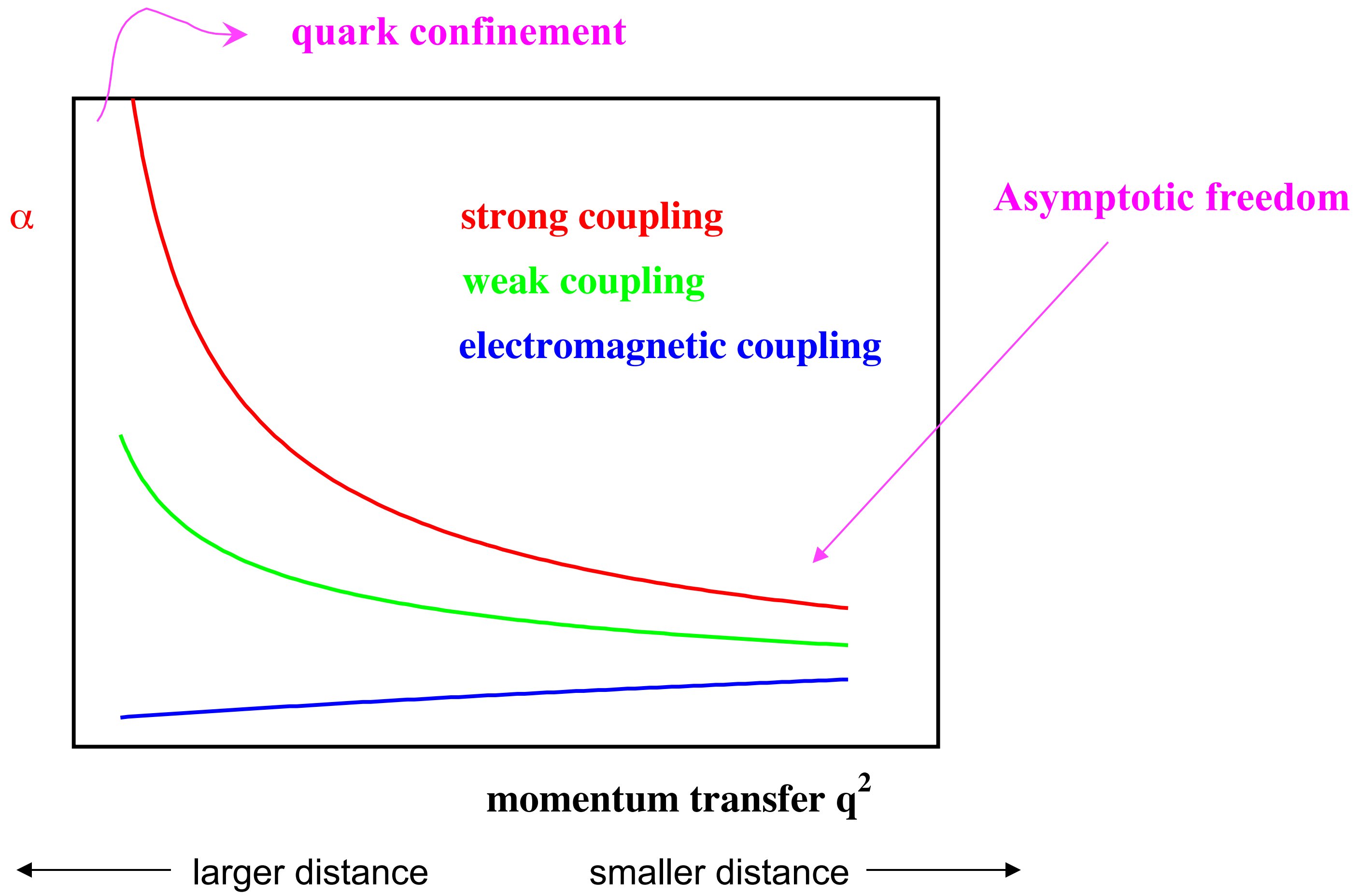
Weak interaction: electroweak gauge bosons carry “weak charge” and so also interact with one another (there are WWZ and WWZZ and WWWW couplings).

These differences have *profound* consequences

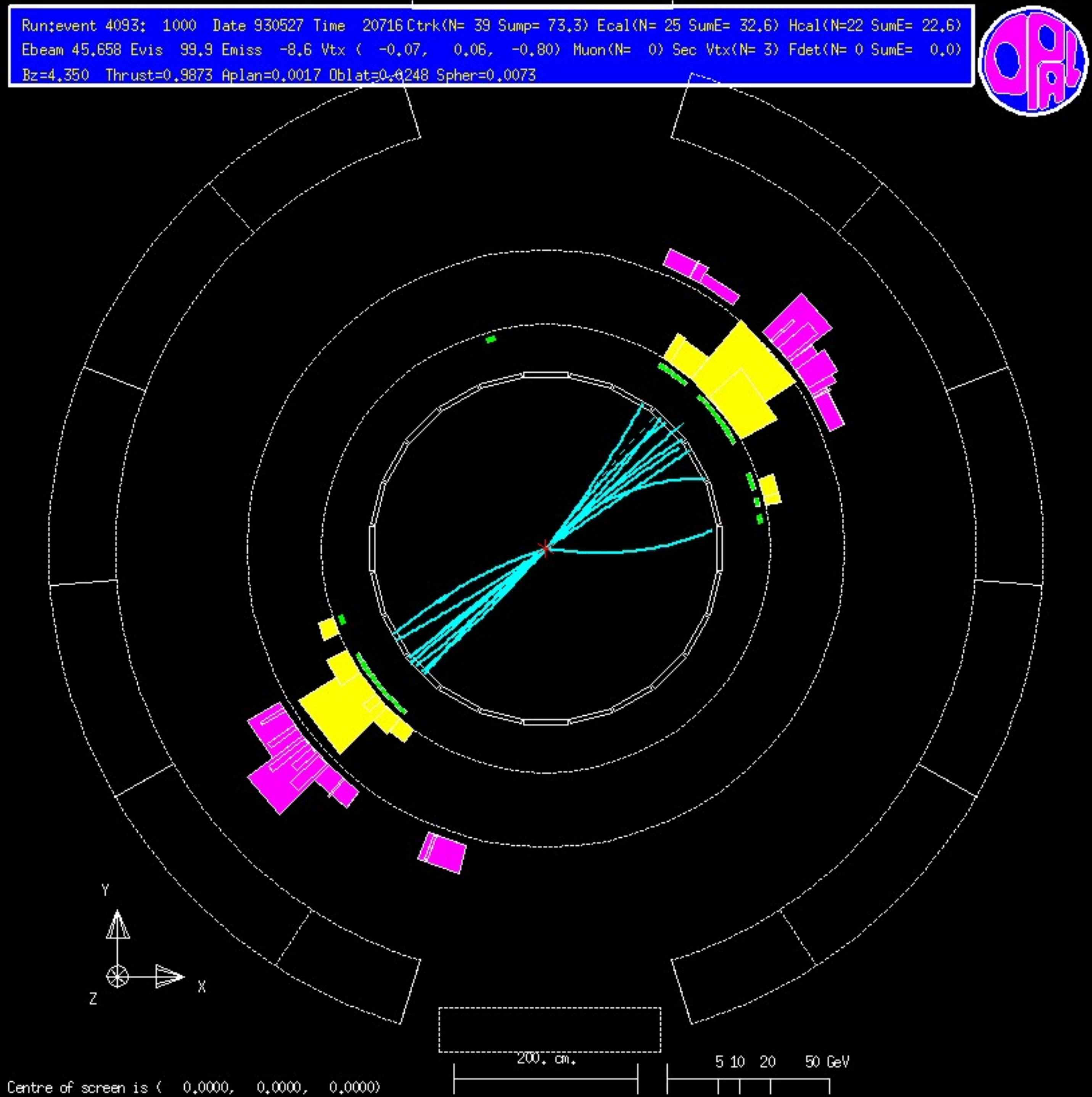
See Griffiths section 2.3 or Halzen & Martin Chapter 1 (which I recommend)

Most importantly, quarks do not exist freely but instead form stable colourless particles called hadrons

Running of Coupling Constants



Momentum transfer is related to the energy at which the interaction is probed.
High q^2 is ~ high energy or small distance scale.



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Bz=4.350  Thrust=0.9873 Aplan=0.0017 Oblat=0.0248 Spher=0.0073
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Centre of screen is (0.0000,   0.0000,   0.0000)

Hadrons from Quarks

- Experimentally: proliferation of hadrons (1960's) lead to the hypothesis that there must be some underlying structure:
  - SU(3) quark model: (u,d,s) quarks, fractional electric charges
    - u   +2/3
    - d   -1/3   anti-quarks are oppositely charged
    - s   -1/3
  - Combinations could explain observed charged and neutral hadrons:
    - Charges of 0 can be made with quark-antiquark combinations
    - Charges of 0,±1 can be made with three quarks or three antiquarks
    - Charge of ±2 can be made with three quarks or three antiquarks
    - Could also (in principle) have larger numbers, but this is not necessary to explain known (e.g. experimentally observed) states.
  - $q\bar{q}$ states are referred to as mesons
  - qqq or $\bar{q}\bar{q}\bar{q}$ states are referred to as baryons (anti-baryons)
  - protons (uud) and neutrons (udd) are the lowest mass baryons
  - Lowest mass mesons are pions ($u\bar{u}$, $u\bar{d}$, $d\bar{u}$, $d\bar{d}$)

group theory

Mesons

- In the SU(3) quark model, one can make nine $q\bar{q}$ combinations:

$$\begin{matrix} u\bar{u} & u\bar{d} & u\bar{s} \\ d\bar{u} & d\bar{d} & d\bar{s} \\ s\bar{u} & s\bar{d} & s\bar{s} \end{matrix}$$

- Get a so-called meson-nonet (9 states) for each spin state:

$$\uparrow\uparrow, \uparrow\downarrow + L = 0,1,2......$$

see § 1.7,1.8

We will come back to this

These are bosons (they have integer spin)

Baryons

- There are 10 three quark combinations:

$$uuu, uud, udd, ddd, uud, uds, dds, uss, dss, sss$$

- Spin combinations:
  - $\uparrow\uparrow\uparrow$ spin 3/2 (get 10 states)
  - $\uparrow\uparrow\downarrow$ spin 1/2 (get 8 states – see below)

all baryons
are fermions

- Different numbers of states for the two spin configurations arises due to requirements on the symmetry properties of the baryon wavefunction which must be anti-symmetric in the exchange of any two quarks.

$$\psi = \psi(space)\psi(spin)\psi(flavour)[\psi(colour)]$$

See § 5.9 (we will not cover chapter much of chapter 5, but will briefly discuss the issue of hadronic wavefuntions in a future lecture.)

Known states

- At the time of the development of the SU(3) quark model, most of the predicted states had already been observed.
- However, one unobserved state was predicted:

$$\Omega^- \equiv sss \quad (\uparrow\uparrow\uparrow)$$

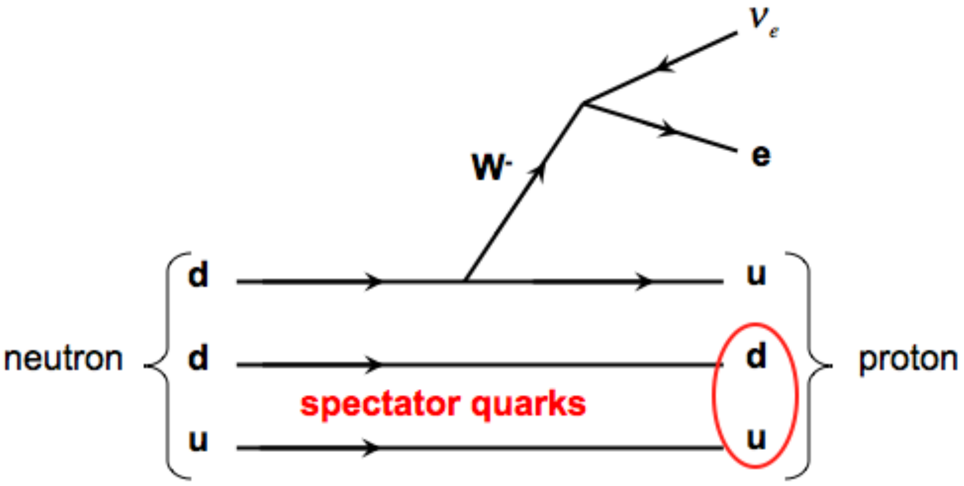
- This was subsequently observed (mass was ~ as predicted)
- Posed and interesting problem (colour not known yet)

$$\psi = \psi(space)\psi(spin)\psi(flavour)[\psi(colour)]$$

- L=0 for ground state (symmetric spatial part); spin and flavour parts are trivially symmetric. So can’t make an anti-symmetric total wavefunction without an additional quantum number: colour.

Feynman Diagrams for Hadron Interactions

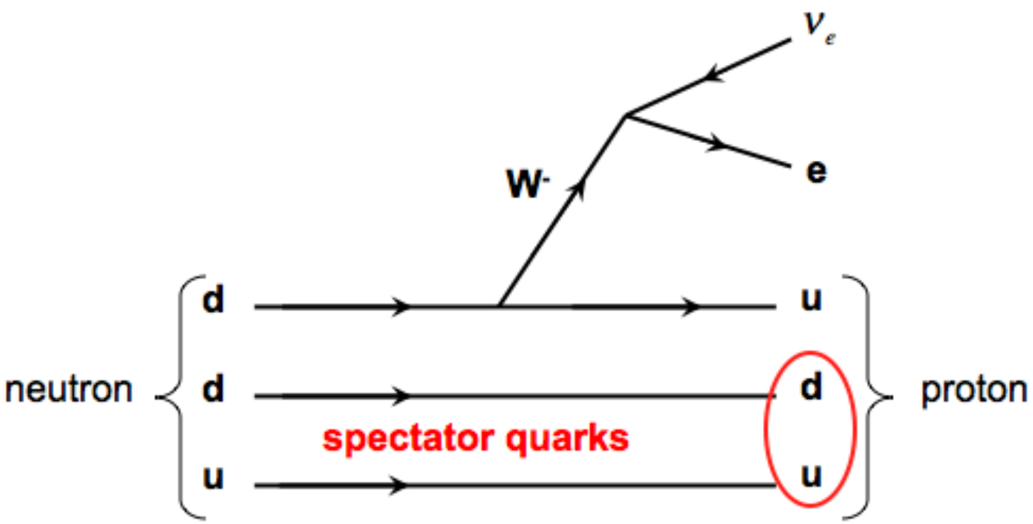
- The preceding material was something of an aside. Really want just to explain the quark structure of hadrons so that we can draw Feynman diagrams for their interactions (mostly decays):



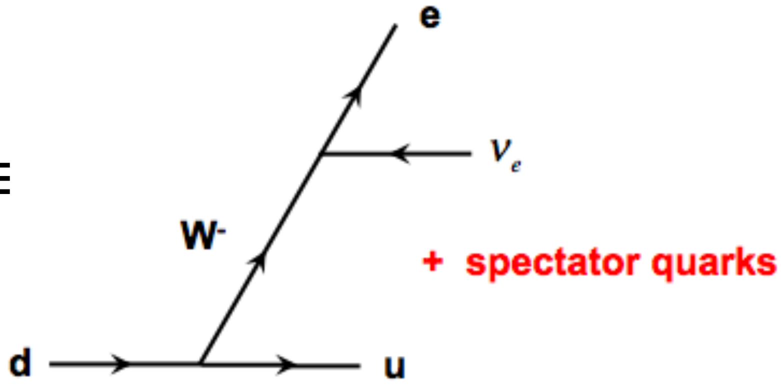
Neutron β-decay $n \rightarrow p \ e^- \ \overline{\nu}_e$

This is a weak interaction process. You can determine this most readily by the presence of a neutrino in the final state, since neutrinos interact ONLY via the weak interaction.

Feynman Diagrams for Hadron Interactions



β decay of a neutron: $n \rightarrow p\, e\, \bar{\nu}_e$ $\equiv$

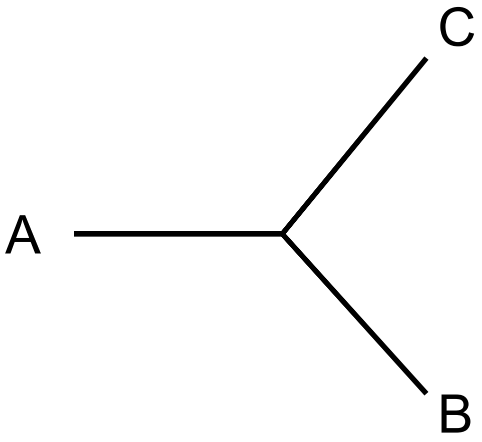


A note on hadronic decays

- We will see later on that the rate at which an unstable particle decays is dependent on the particle mass, with heavier particles typically decaying faster than light ones. In the decay of a hadron containing an heavy quark (i.e. not u or d) if the decay involves a quark flavour change (which can occur only via the charged weak interaction) the decay always is due to the heaviest quark decaying to a lighter one.
- Will do example on blackboard: B meson decays.
- We will discuss the pattern of such decays in the next lecture.

Particle Decays

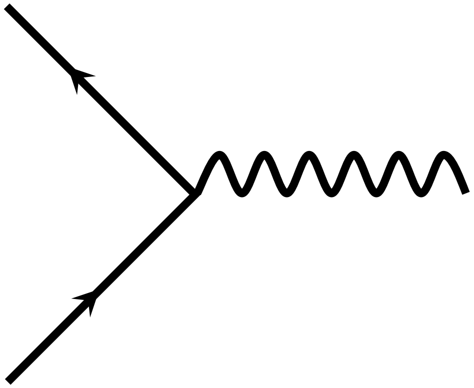
- Every particle will decay into lighter particles unless forbidden to do so by some conservation law.
- “Kinematics” arise from the applications of the rules of conservation of energy and momentum.



The decay A → B + C is kinematically forbidden if $M_A < M_B + M_C$

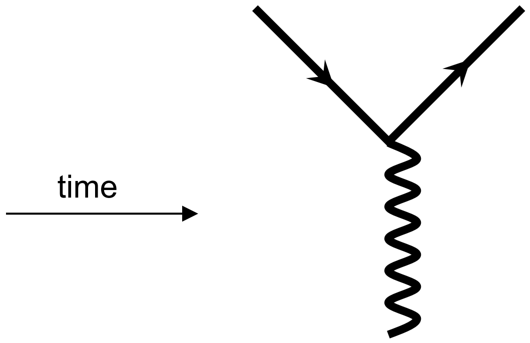
If masses are such that none of these particles can decay into the other two, this can still contribute to scattering processes (we will see this for QED).

Processes in Quantum Electrodynamics (QED)

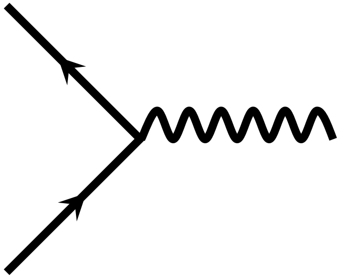


QED contains only a single fundamental interaction: that of a photon with an electron.

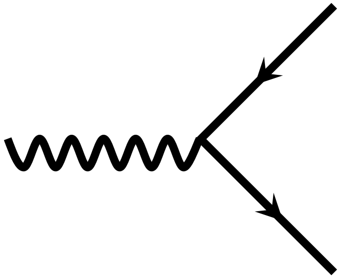
This does NOT, however, represent any real *process*



$e^- \to e^-\gamma$

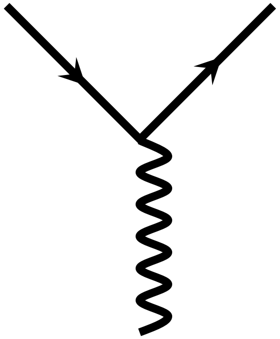


$e^+e^- \to \gamma$

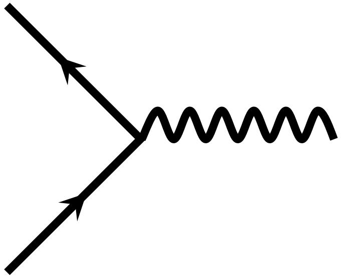


$\gamma \to e^+e^-$

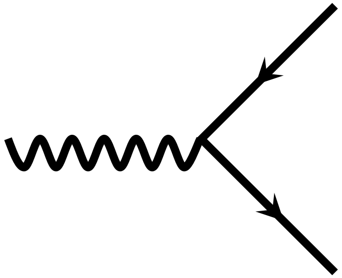
Processes in Quantum Electrodynamics (QED)



$e^- \rightarrow e^-\gamma$: as a *process* this is forbidden by conservation of energy, Lorentz invariance.



$e^+e^- \rightarrow \gamma$: as a *process* this is forbidden by cons. of momentum, Lorentz invariance

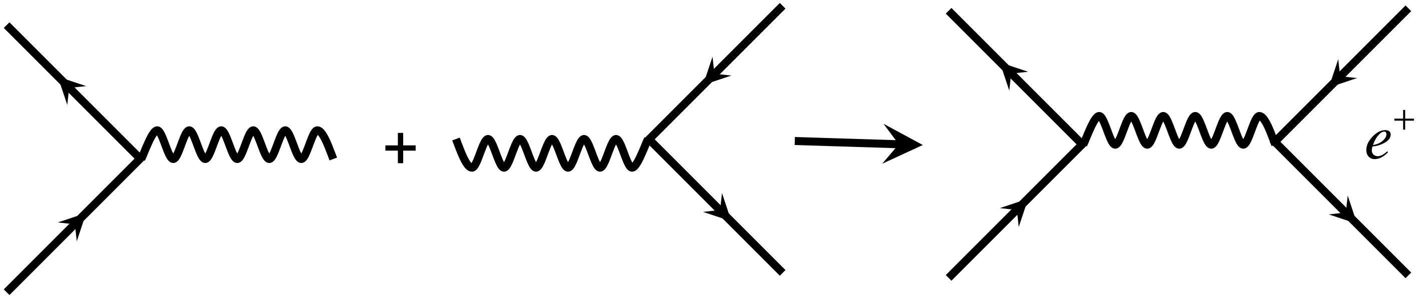


$\gamma \rightarrow e^+e^-$: as a *process* this is likewise forbidden

See discussion in section 2.2. Despite the fact that the primitive vertices do not represent allowed processes, they can appear in more complex (e.g. scattering) diagrams

Processes in Quantum Electrodynamics (QED)

All allowed processes in QED are made up of combinations of this single fundamental vertex



$$e^+e^- \rightarrow \gamma^* \rightarrow e^+e^-$$

γ^* denotes a *virtual* photon

We will define this

A virtual particle takes on whatever mass is required by conservation laws. Here the γ^* has a mass that corresponds to the invariant mass of the initial- (and final-) state particles. The * is not usually drawn, except where there is a need to be explicit.

Particle Lifetimes

- Each fundamental interaction has an associated timescale over which it takes place (we will understand the reasons for this later in the course):
  - Strong interaction: 10^{-23} s
  - Electromagnetic interaction: 10^{-16} s
  - Weak interaction: 10^{-13} s up to ~ 15 minutes

for the decay of a free neutron

- These timescales are related to the effective coupling strengths of the interactions (the stronger the coupling the faster the interaction). These timescales are most meaningful when talking about particle lifetimes.
- Lifetime usually denoted by symbol τ.

Particle Lifetimes Cont’d

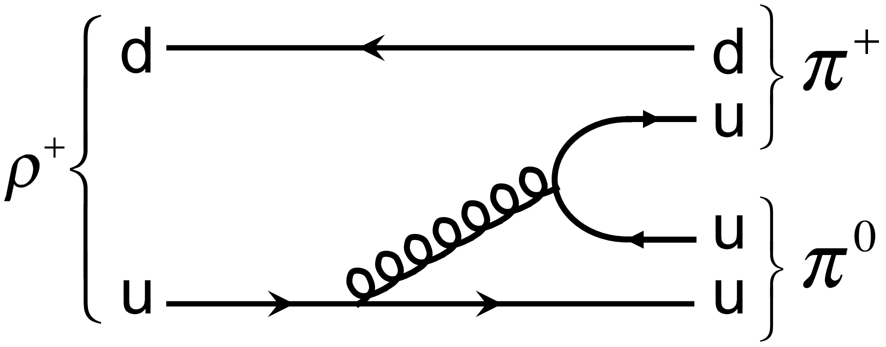
- Generally, if you are asked via which interaction some process proceeds sometimes the answer is clear:
  - if photons are involved it is (generally) electromagnetic (there are exceptions).
  - if neutrinos are involved it is weak (there are no exceptions).
- Sometimes it is less clear, usually in processes involving hadrons. Here’s a good initial rule of thumb:
  - If it can proceed via the strong interaction it will, and this will dominate regardless of whether it can *also* proceed via the EM or weak interaction, since the strong interaction occurs so much faster. A strong decay is always hadron → hadrons.
  - If the strong interaction is forbidden, then if the process can occur via the EM interaction, that interaction will dominate.
  - The weak interaction will dominate (or contribute significantly) only when the other two interactions cannot contribute.

Examples: Decays of Light $u\bar{d}$ Mesons

$\rho^+(770) \equiv u\bar{d}\ (\uparrow\uparrow)$ Spin 1 (vector) meson, mass = 770 MeV/c^2

$\rho^+ \to \pi^+\pi^0$ Dominates the decay since the state is massive enough to decay to lighter hadrons: $\tau \sim 10^{-23}$ s.

Internal lines consist of gluons only so this is a strong interaction.



$\pi^+ \equiv u\bar{d}\ (\uparrow\downarrow)$

Spin 0, mass = 139.6 MeV/c^2

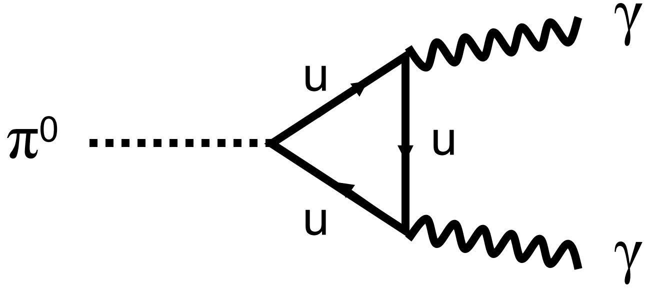
$\pi^0 \equiv u\bar{u}, d\bar{d}\ (\uparrow\downarrow)$

Spin 0, mass = 135.0 MeV/c^2

Pions are the lightest hadrons and so cannot decay strongly.

Decays of the neutral pion π^0

- Can it decay via strong interaction ? NO (no lighter hadron)
- Can it decay via the EM interaction ? YES !
- Diagram is a little complicated (don’t need to remember this).

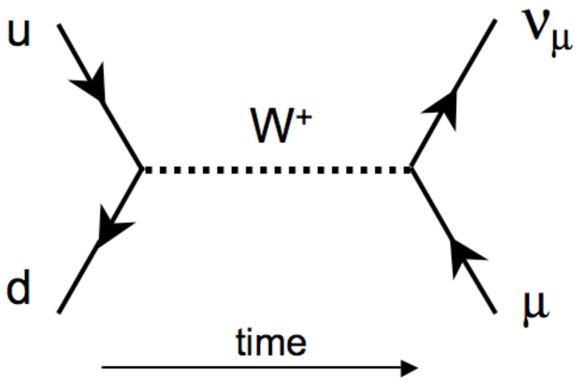


$\tau \sim 10^{-16}$ s

We will see this decay again when we discuss conservation laws.

Decays of the charged pion π^+

- Cannot decay via strong interaction (no lighter hadrons except π^0 but need two hadrons in the final state and charge must be conserved).
- Cannot decay electromagnetically: would have to be neutral or there would need to be a lighter charged hadron with the same quark content.
- Decays only via the weak interaction: $\pi^+ \to \mu^+ \nu_\mu$ $\tau \sim 10^{-8}$ s



This is kind of cheating, since the initial state quarks are bound inside the pion. But we will come back to this later on.

A comment on the text

- Griffiths at one point uses the term “disintegration” when referring to particle decay. I find this word misleading because it implies a “falling apart” rather than a transition (or a “coupling” between one type of particle and another).

Next lecture: finish with introduction to the Standard Model.

Wednesday Sept. 18: start relativistic kinematics (Chapter 3)

You should have read chapters 1 and 2 by then.